What New Liquefaction Can Teach Us About Old Earthquakes: Evaluating the Efficacy of Paleoliquefaction Analytics using Modern Analogs

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BACKGROUND

- The use of paleoliquefaction evidence to assess seismic hazards has become increasingly common, particularly in regions of infrequent but potentially damaging seismicity.
- This technique involves locating liquefaction features induced by prehistoric or pre-instrumental earthquakes and using quantitative back-analysis methods to estimate the causative ground motion and earthquake magnitude.

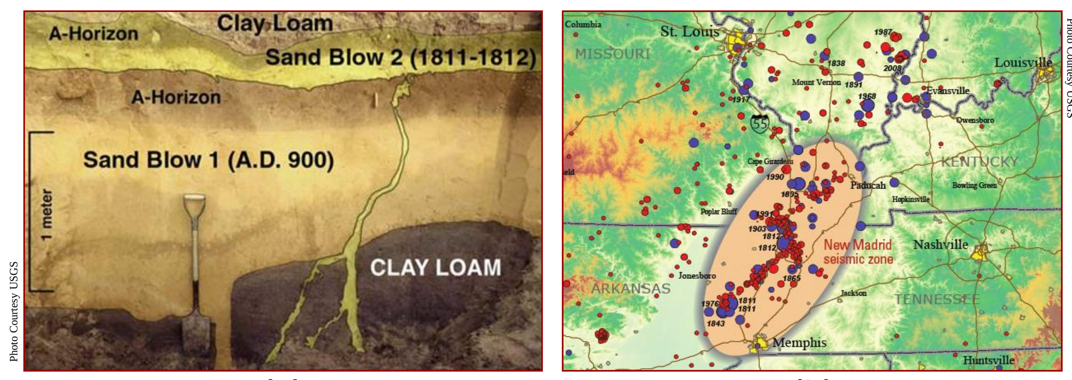

Fig 1. (a) Paleoliquefaction feature from the New Madrid Seismic Zone (NMSZ); (b) Overview of the NMSZ and Central-Eastern U.S. (CEUS) seismicity.

- Paleoliquefaction studies elucidate seismic records as far back as Pleistocene time, providing data for seismic hazard evaluations. Such studies have been performed at sites worldwide, in addition to many in the United States:

Table 1. Regions of Paleoliquefaction Study in the U.S.

Seismic Zone (Location)	Study
New Madrid (MO, AR, TN)	Tuttle et al., 2005
Wabash Valley (IL, IN)	Obermeier, 1998
Charleston Coastal Plain (SC)	Talwani & Schaeffer, 2001
Cascadia Subduction (OR, WA)	Obermeier & Dickinson, 2000
San Diego (CA)	Kuhn, 2005
Clarendon (NY)	Tuttle et al., 2002
South-Central Illinois (IL, MO)	McNulty & Obermeier, 1999
Cape Ann (MA)	Ellis & de Alba, 1999
Mississippi Embayment (AR)	Cox et al., 2004

- While computed seismic hazards are in some regions founded largely on paleoliquefaction data, back-analyses are subject to **numerous uncertainties** and their **accuracy is unknown**; these techniques have never been assessed using modern earthquakes with known magnitudes.
- Thus, the **efficacy** of paleoliquefaction back-analyses and **accuracy** of derivative seismic hazard assessments for regions around the world are **uncertain**.
- The 2010-2011 Canterbury earthquakes demonstrate the potential consequences of seismic hazard uncertainty. The geomorphology of deposits, severity of liquefaction, and relative timing of events also make them analogous to many paleo-earthquake clusters (e.g., 1811-1812 NMSZ).

OBJECTIVE

- **This study aims to evaluate our capacity for estimating earthquake magnitudes from liquefaction data by back-calculating the magnitudes of the 2010 Darfield and 2011 Christchurch (NZ) earthquakes and comparing with the actual magnitudes; a novel analysis framework for paleoliquefaction interpretation is proposed & assessed.**
- It is hypothesized that this study will help resolve the accuracy of paleoliquefaction analysis techniques and identify mechanisms for improving paleomagnitude estimates by providing the first such assessment to-date.

DATA AND METHODOLOGY

The Canterbury earthquakes present a unique opportunity to assess the accuracy of paleoliquefaction back-analyses. Towards this end, simulated paleoliquefaction studies of the Darfield and Christchurch earthquakes are performed. Following a summary of the Canterbury earthquakes, the "site-specific geotechnical analysis" is outlined, and its application to the Canterbury sequence is discussed.

1. Canterbury Earthquake Sequence

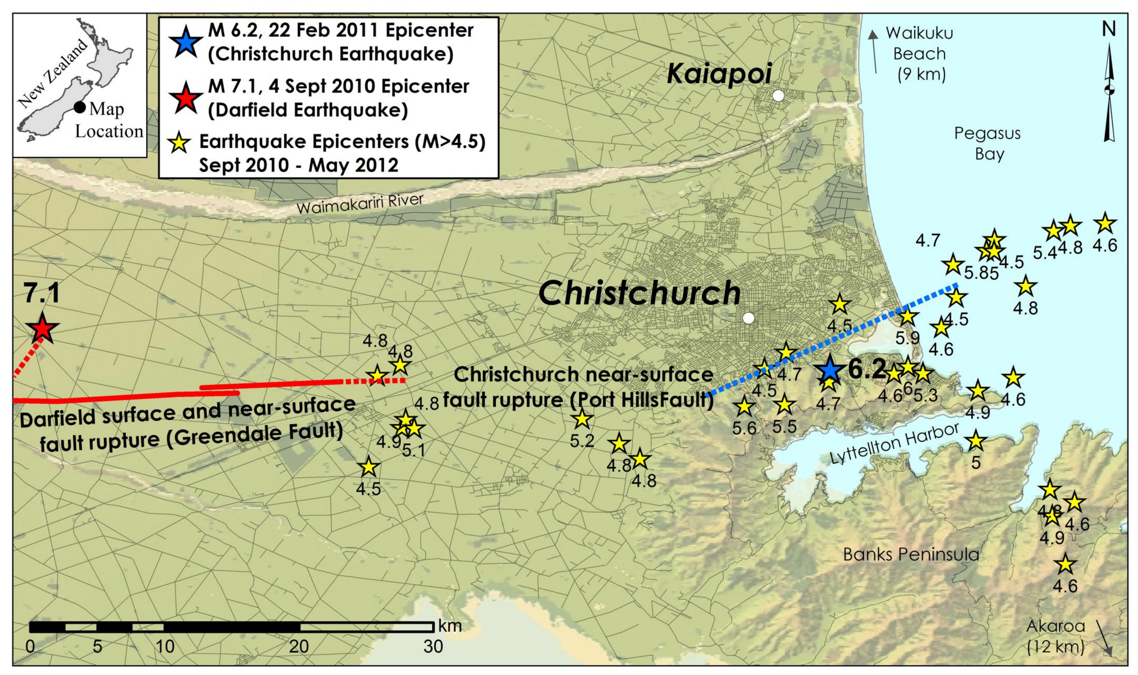

Fig 2. Overview of the Canterbury earthquake sequence

Fig 3. Liquefaction effects during the Canterbury sequence

2. Site-Specific Geotechnical Paleoliquefaction Analysis

- Evaluates sites across a broad region to estimate the causative ground motion & earthquake magnitude.

Back-Analysis Procedure at Investigation Site:

I. The "critical" strata within the profile is assumed to have a factor of safety against liquefaction of 1.0:

$$FS_{liq} = \frac{CRR}{CSR_{7.5}} = 1.0 \quad (1)$$

II. Substituting for CRR and $CSR_{7.5}$ as defined by the simplified procedure (Seed & Idriss, 1971), the minimum PGA to induce liquefaction is expressed as:

$$a_{max} = CRR(q_{1N,cs})MSF(M_w)K_\sigma \frac{g\sigma'_{vo}}{0.65\sigma_{vo}r_d} \quad (2)$$

III. The boundary given by Eq. (2) identifies combinations of $a_{max} - M_w$ sufficient to trigger liquefaction (Fig. 4a)

IV. A ground motion prediction equation (GMPE) is used to define credible $a_{max} - M_w$ combinations for a site with given site-to-source distance, R (Fig. 4b)

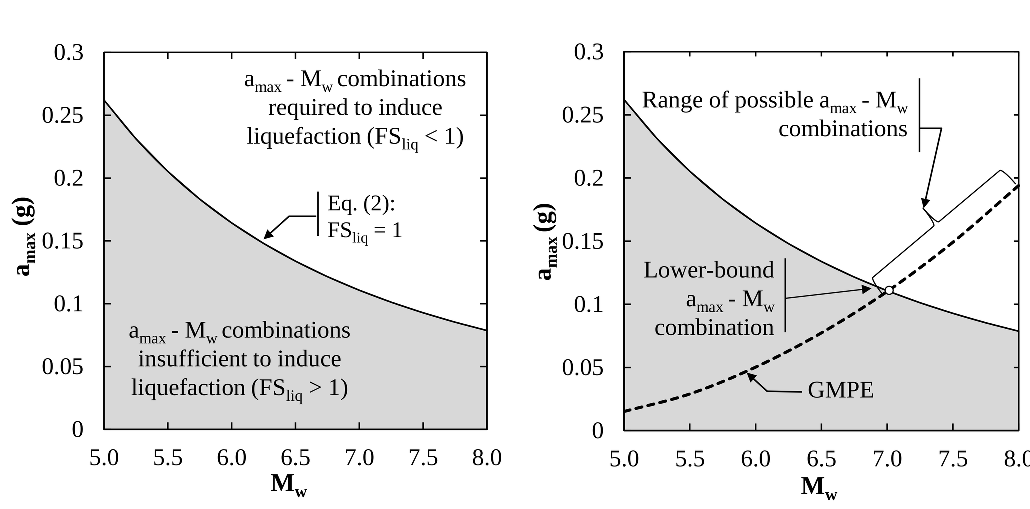

Fig 4. Determination of lower-bound $a_{max} - M_w$ combination for paleoliquefaction investigation site

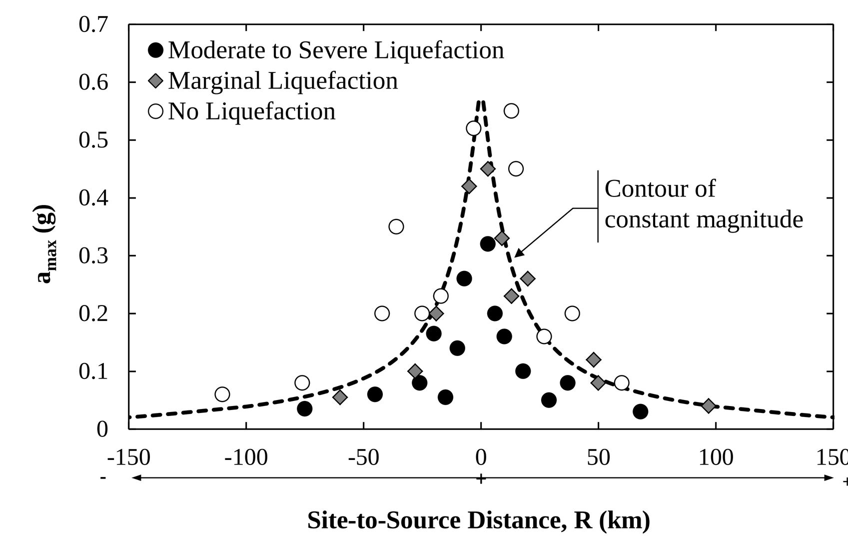

Fig 5. Proposed regional assessment of back-calculated data

V. Back-calculations at liquefaction sites give minimum earthquake magnitude; repeating at sites without liquefaction gives maximum earthquake magnitude

VI. To obtain a best-estimate of the causative earthquake magnitude, individual back-analyses are incorporated from many sites across the affected region (Fig. 5)

VII. Causative magnitude is that which best segregates liquefaction data from non-liquefaction data (Fig. 5) using Error Minimization Function, E_f

3. Application to the Canterbury Earthquake Sequence

- 75 study sites randomly selected from the Canterbury database to simulate paleoliquefaction study
- FS_{liq} computed from Robertson and Wride (1998)
- 5 GMPEs used in back-calculations: McVerry et al. (McV06) ; Boore & Atkinson (BA08); Chiou & Youngs (CY08); Abrahamson & Silva (AS08); and Bradley (B10)
- Analysis performed assuming both known & unknown earthquake source locations & rupture mechanisms

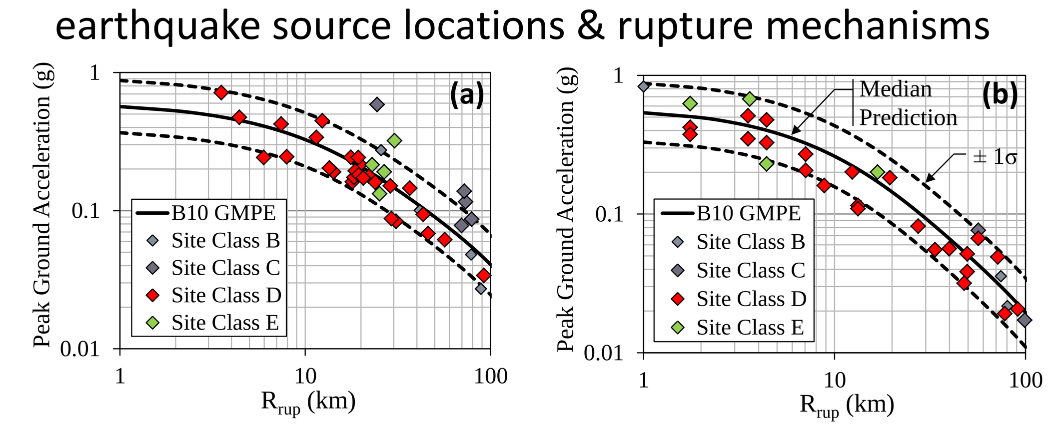

Fig 6. Bradley GMPE (Site Class D) vs. recorded PGA values in the (a) Darfield and (b) Christchurch earthquakes

RESULTS AND DISCUSSION

1. Assuming known rupture location & mechanism (Fig. 2)

- Used published source models for each earthquake

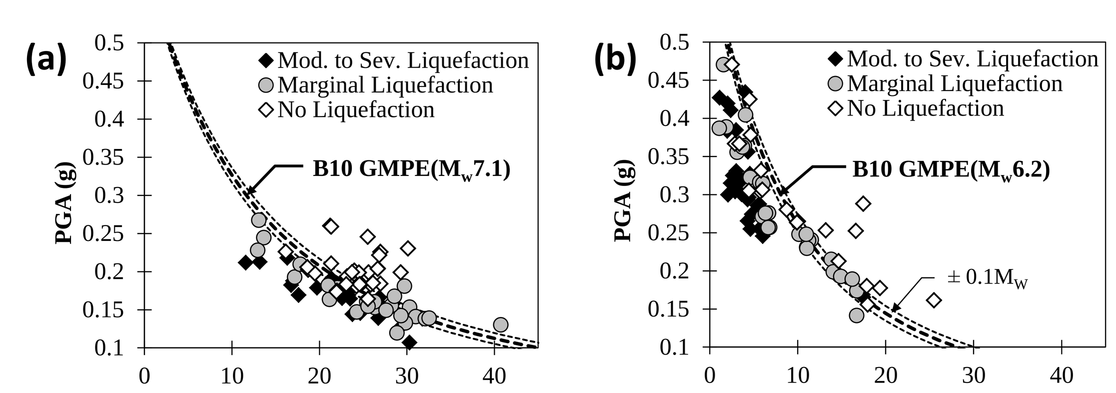

Fig 7. Assessment of the causative earthquake using the B10 GMPE for the (a) Darfield and (b) Christchurch EQs

Table 2. Summary of Results – Known Source Locations

	Darfield (M_w7.1)		Christchurch (M_w6.2)	
GMPE	Estimated M_w	Estimate Error (%)	Estimated M_w	Estimate Error (%)
BA08	6.90	-2.8	6.45	3.5
McV06	7.16	0.8	6.30	1.4
CY08	7.15	0.7	6.22	0.3
AS08	7.21	1.5	6.41	3.0
B10	**7.12**	**0.3**	**6.20**	**0.0**

2. Assuming unknown rupture locations & mechanisms

- While the site-specific analysis performed very well with known earthquake source locations/models, these are often unknown in paleoseismic investigations.
- In this case, a strike-slip mechanism is assumed and the source is modeled at 1 km depth; used B10 GMPE.
- The objective index E_f allows for the automated processing of infinitely many potential source locations; an analyst can geospatially assess the likelihood of any source location considering normalized E_f and the corresponding estimate of earthquake magnitude:

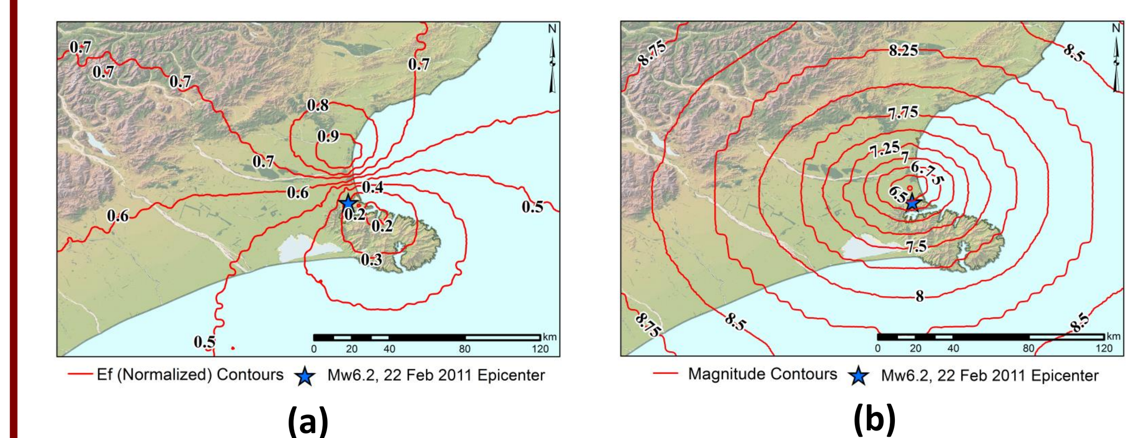

Fig 8. Spatial distribution of (a) normalized E_f and (b) best-estimate magnitudes for the Christchurch earthquake

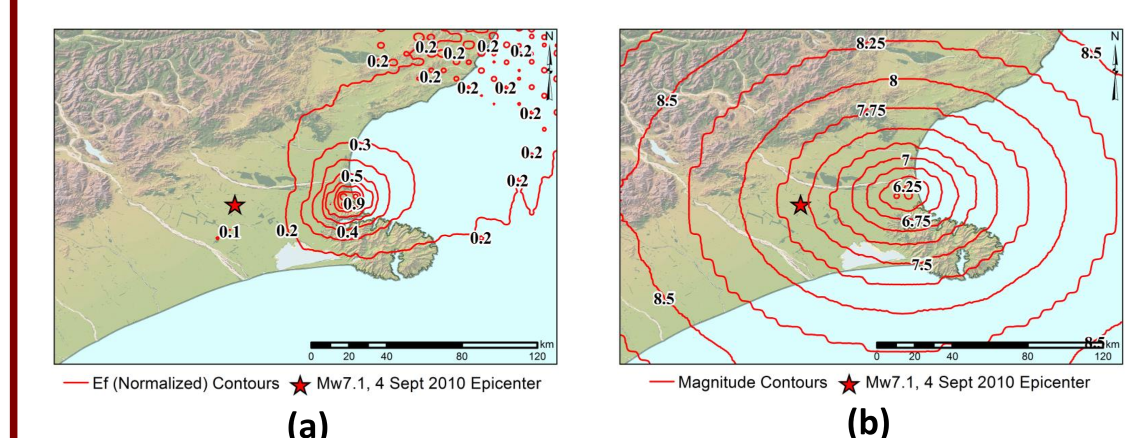

Fig 9. Spatial distribution of (a) normalized E_f and (b) best-estimate magnitudes for the Darfield earthquake

- Grid-Search technique (Fig 8) accurately identified actual source region of the Christchurch earthquake; Source region of Darfield earthquake not well-bounded but analysis (Fig 9) suggests M_w > 7.0.
- Best-estimate magnitudes differ from actual magnitudes due to errors in most-likely source location.
- Sensitivity of results to the number of sites used in analysis (Fig 10) indicates that: (1) only ~10 sites are needed for stable solution with known source location; and (2) 35-60 sites required for stable solution if source locations unknown (implications for field studies).

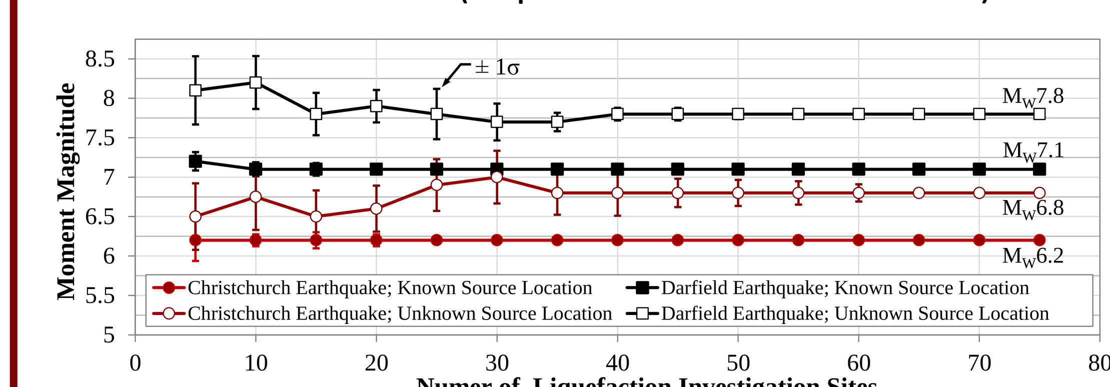

Fig 10. Sensitivity of back-calculated earthquake magnitudes to the number of investigation sites used in analysis

CONCLUSIONS

1. Paleoliquefaction back-analyses can be very accurate if earthquake source location & mechanism are known.
2. Accurate analysis is more difficult if source location is unknown, but index E_f enables more intelligent estimate of causative earthquake's location and magnitude.
3. Framework using site-specific geotechnical analysis shown to be effective and proposed for use in paleoliquefaction studies worldwide.